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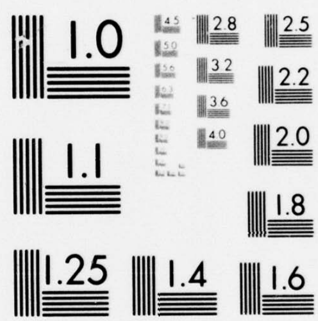
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A SMALL TURBOCHARGER ENGINE.

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Michael O'Brien
1st Lt. USAF

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PERFORMANCE EVALUATION OF A SMALL TURBOCHARGER ENGINE

THESIS

Presented to the Faculty of the School of Engineering

Of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

Michael O'Brien, B.S.M.E.

1st Lt. USAF

Graduate Aeronautical Engineering

March, 1978

PREFACE

This thesis project continues the work done previously to develop a low cost, expendable turbojet engine. A possible application is as a power plant for remotely piloted vehicles (RPV's). The concept is to minimize cost using existing components whenever possible. Many RPV designs call for a one-way flight. In these cases, it is obviously desirable to have an inexpensive engine with a limited operational life.

To examine this concept, an automotive turbo supercharger was mated with a simple combustor using a catalytic element. The materials used are not very exotic and the fabrication techniques available were basic. A critical evaluation of the resulting engine may show some inferiority to a production turbojet engine in terms of absolute parameters. However, when compared on a basis of performance delivered per unit cost, this engine concept will come out far ahead.

In this project, invaluable support was given by the AFIT model shop led by Mr. Carl Shortt. They produced most of the parts used and abused during testing. The shop personnel was extremely responsive to all our needs. Basic direction was provided by Dr. William C. Elrod, my primary advisor. Day to day assistance at the lab was given by John Parks. The other members of my committee were Dr. Harold E. Wright and Captain Richard A. Merz.

Mr. David Wilkinson of the Air Force Aero Propulsion Laboratory gave additional support. Special thanks go to Larry Taylor and Robert Barham who shared the unique experiences that were a part of working in the lab.

Michael O'Brien

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List of Symbols

Symbol	Quantity	Units
A/R	Aspect ratio of turbine housing	--
F_n	Thrust	lb.
$\dot{M}$	Mass flow rate	lb/hr
P	Pressure	lb/in^2
P_{rc}	Compressor pressure ratio	--
RPM	Engine rotation speed	rev/min
T	Temperature	F
δ	Pressure correction	--
Δ	Difference	--
θ	Temperature correction	--

Subscripts

∞	Ambient condition
1	Hydrogen line upstream of venturi
2	Hydrogen line downstream of venturi
3	Engine station between compressor and combustor
4	Turbine inlet station
5	Engine station at rear of turbine
a	Air
c	Corrected
d	Engine station in combustor at rear

Abstract

Performance data were taken for a small turbojet engine which is made up of a turbo supercharger and a catalytic combustor, which were originally intended for automotive use. The design employed the catalyst to promote a hydrogen reaction in air to power the rotating machinery. Several turbine housings each used with various nozzles were run on the engine to produce performance data. Using a turbine inlet temperature limit of 1800F and a rotating speed limit of 120,000 RPM, a maximum thrust of 34 lb. was recorded. Stable engine operation was observed in most configurations. Performance compared well with theoretical data supplied by the CARPET computer program.

PERFORMANCE EVALUATION OF
A SMALL TURBOCHARGER ENGINE

I. Introduction

Background

The development of small, low-cost turbojet engines has been undertaken by AFIT for some time. The principal component being a mass produced turbo supercharger originally intended for automotive use. Components used were commercially available and inexpensive, at least in aircraft terms; other parts were fabricated using simple techniques and non-exotic materials. The cost savings per pound of thrust delivered in such a system were significant (Ref 10).

The earliest work demonstrated the basic feasibility of such an engine. A Rajay 370-E turbocharger was fitted with a simple combustor to produce the first engine (Ref 7). More advanced instrumentation was developed for work on a larger turbocharger engine (Ref 6). This instrumentation was used in all subsequent work. Also, the feasibility of using a catalytic converter as a combustor was demonstrated on the turbocharger used previously (Ref 5). Hydrogen gas was the chosen fuel since it reacts with the catalyst under ambient conditions. However, there was no opportunity to obtain performance data.

Objectives

The principal aim of this study is to generate performance data on the small turbocharger engine using a new combustor featuring a catalytic element. The original catalytic burner had a problem with flame propagation upstream of the catalytic element. A new combustor was to be designed to eliminate this problem. The new combustor will provide a region for the hydrogen reaction once it is started by the catalyst. This should prevent the reaction from moving upstream of the combustor. In starting the engine, it will be necessary to have the reaction propagate a short distance upstream of the catalyst for stable operation. A new turbine housing was designed to be fabricated by the AFIT shop. The reason was to test the feasibility of reducing weight without sacrificing performance. Tests will be run to compare its performance to the other engine data. The data generated will be compared to theoretical values obtained from the CARPET program (Ref 13).

Scope

A workable engine configuration and instrumentation was prepared to generate performance data. The engine was tested with four turbine housings and four nozzles. The technique was to fit the largest turbine housing and run first with no nozzle providing an exit diameter of 2 3/4 in. Each nozzle was in turn fitted and run in order of decreasing size.

This procedure was repeated for each standard turbine housing. Basic performance data was collected for each engine configuration. The effect of housing and nozzle size was to be evaluated in terms of turbine inlet temperature, thrust, air mass flow, compressor pressure ratio, and the speed of rotation. These are basic parameters useful in judging engine performance.

The basic arrangement of the turbocharger engine will be described. Then the test apparatus used will be covered. This is followed by the general operational procedure. The results obtained will be shown and discussed. Extra information concerning data reduction will be found in Appendix A.

II. Engine Arrangement

Turbo Supercharger

The heart of the engine is the Rajay 370-E turbocharger. As used in this testing, the unit consisted of a cartridge, containing the bearings and rotating parts; a compressor housing; and one of several turbine housings available. The size of the turbine housing is denoted by the A/R ratio (Ref 5:33). Four production housings were used with A/R ratios of .7, .8, .9 and 1.0. The A/R ratio is a size parameter for turbine housings defined as the inlet area divided by the radial distance from the center of the inlet to the shaft centerline. Another housing designed for testing was fabricated by the AFIT Model Shop by welding pieces of stainless steel together. The basic turbocharger is illustrated in Figure 1. Further information and exact specifications may be obtained from Reference 11.

Combustor

The combustor used in this testing is a new unit utilizing a catalytic bed, taken from a Ford catalytic converter Model 5 E 212. The combustor, as shown in Figure 2, is basically a reverse-flow device utilizing the catalytic reaction to provide the necessary conditions to initiate the hydrogen reaction. The catalyst also assures completion of the combustor reaction before entering

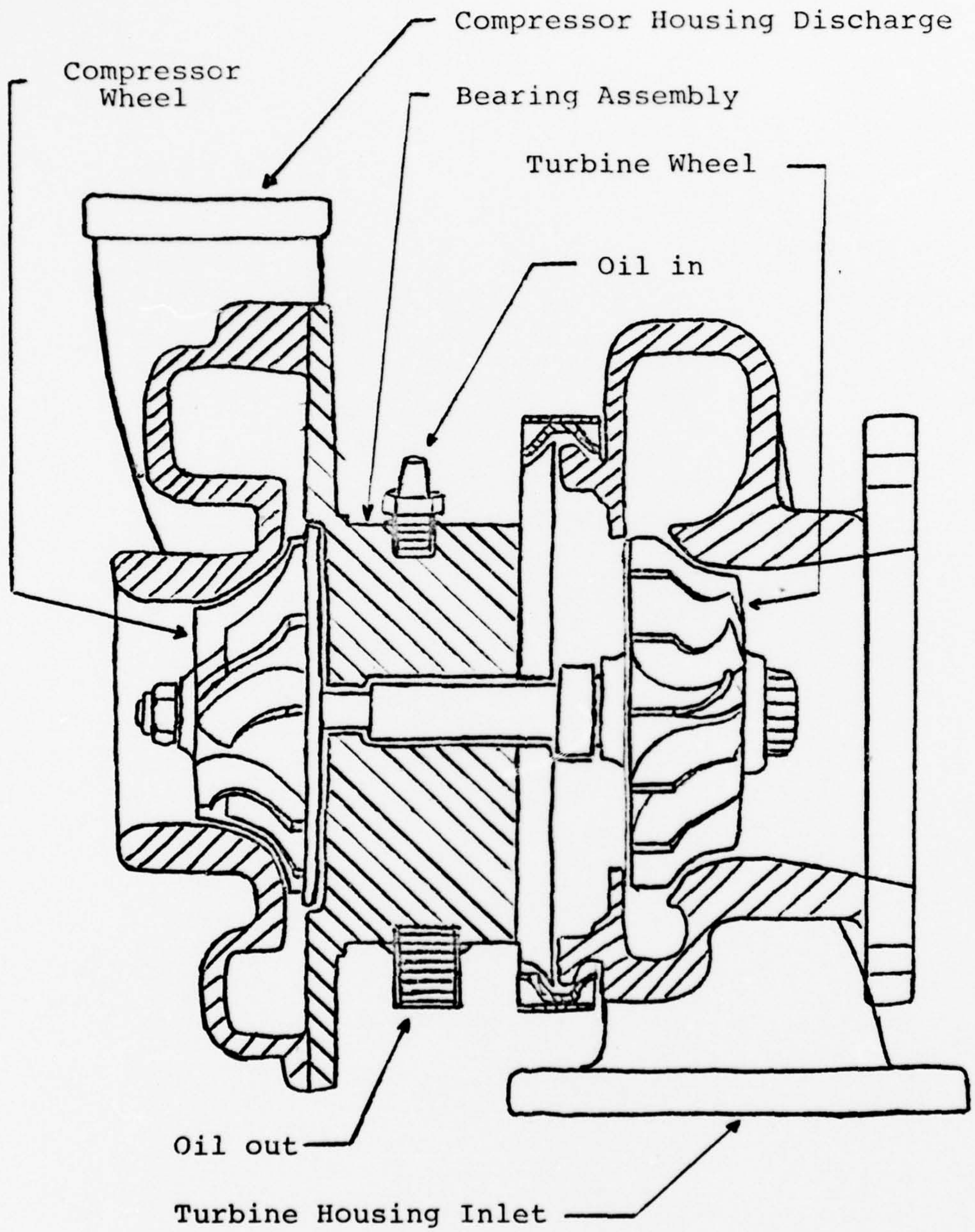


Figure 1. Basic Turbocharger Arrangement

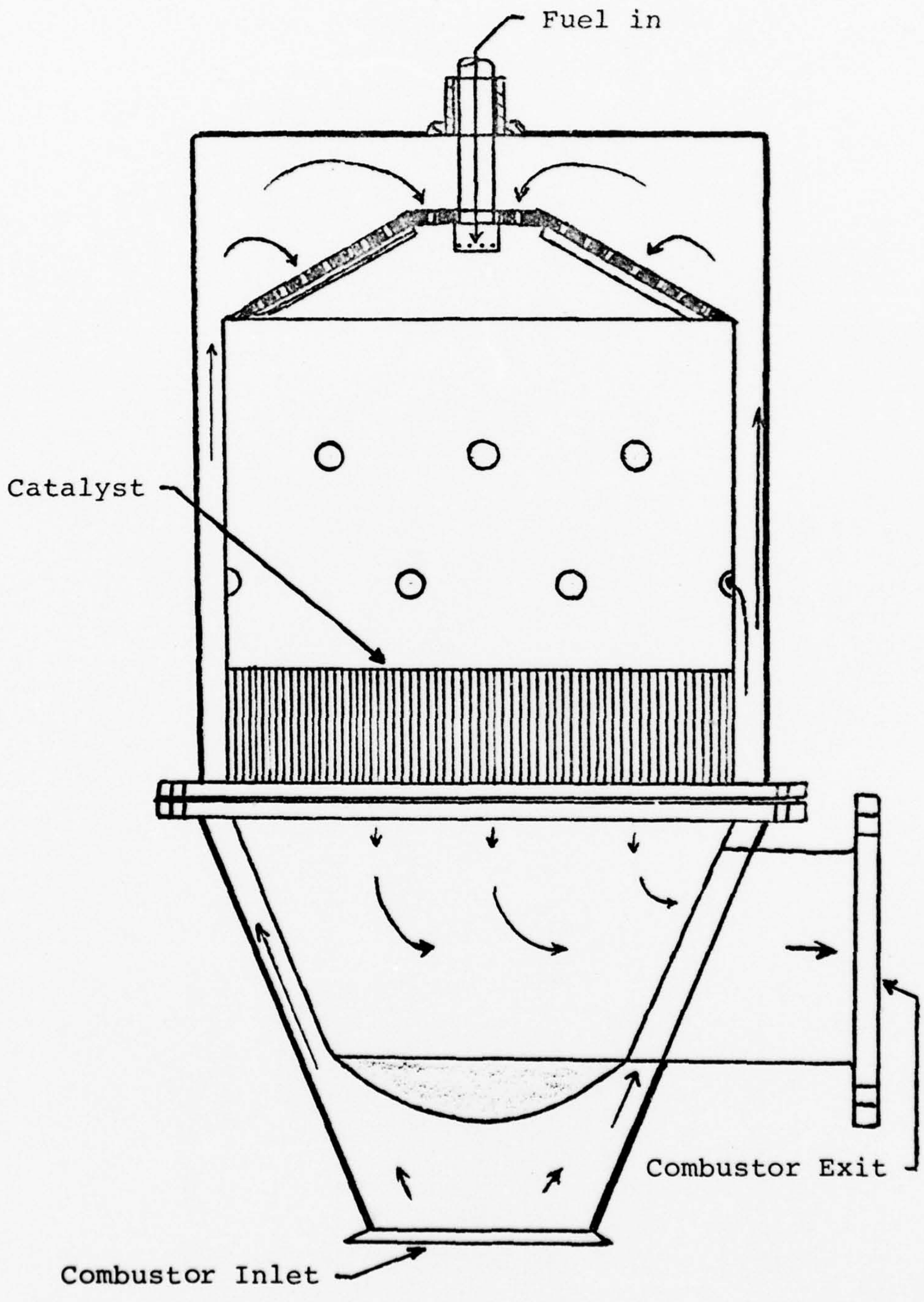


Figure 2. Combustor

the turbine. The fuel enters the rear of the combustor through a stainless steel pipe leading to the injector nozzle inside the inner liner. Air flow is provided through holes in the liner top and dilution holes in the sides of the liner.

Engine Configuration

The combustor exit was directly attached to the turbine housing inlet flange (Fig. 3). The compressor discharge was connected to the combustor inlet by means of two stainless steel pipe sections attached with fiber-reinforced rubber hose. Clamps and safety wiring were used to assure engine integrity. A bellmouth inlet was attached to the compressor inlet and the nozzle, if used, was clamped to a constant area instrument section which in turn was bolted to the turbine housing.

Lubrication System

It is vital during engine operation to keep oil circulating through the bearing assembly of the turbocharger. It provides cooling as well as lubrication. A 1/6 horsepower DC motor keeps the five-quart supply circulating adequately during operation. Reference 5 describes this system in detail.

Fuel System

The engine was fueled with hydrogen which, like the other compressed gases used in quantity, was supplied by a trailer parked outside the lab building. The hydrogen

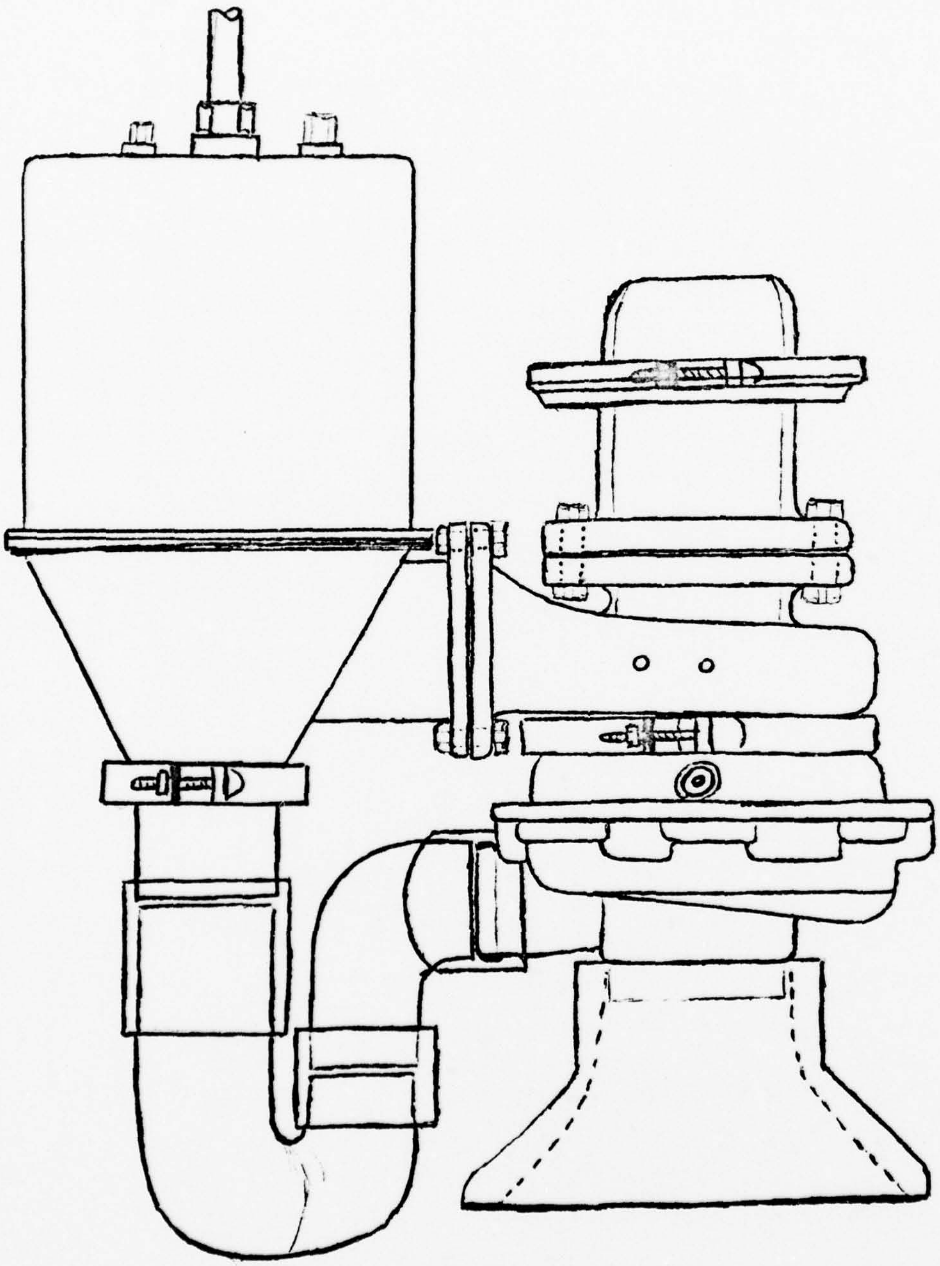


Figure 3. Engine Arrangement

was brought into the building through pipes which led right to the engine through a dome regulator valve. There was a venturi flowmeter installed by Jahnke (Ref 9) with manometer connections across it. A pressure transducer was used to record the pressure downstream of the venturi, the output of which was recorded by the CEC oscillograph. The injector nozzle was a simple cylindrical cap with angled holes drilled through it. The hydrogen was introduced just under the liner dome about five inches from the catalyst.

Starting

The engine is started by impinging compressed air or nitrogen on the turbine blades to bring the rotating parts to a speed sufficient for self-sustained operation when fuel was added. Each turbine housing has an air-start pipe and fitting installed for this purpose. The air-start system is also used to motor the engine for cooling after the fuel flow is cut off.

Control

Principal control is through dome valves located in the control room. One valve regulates the air pressure for starting and cooling the engine. Hydrogen fuel pressure is controlled by another valve. The engine speed and turbine inlet temperature are monitored to show the effects of control inputs. For emergency shut-down, as well as normal termination of a run, a nitrogen purge system serves

to cut off the fuel flow and pass nitrogen gas through the combustor when a switch is thrown. The purge pressure is also controlled by a valve in the control room.

III. Engine Test Apparatus

Temperature Measurement

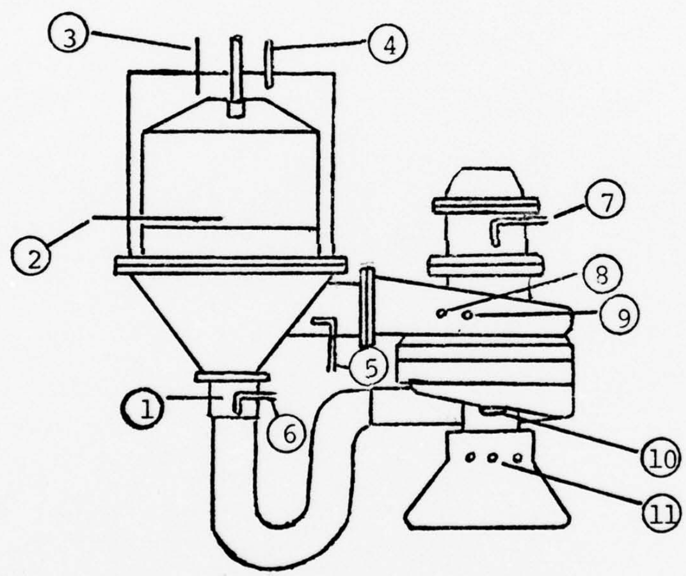
Thermocouples were utilized to measure engine temperature at various locations (Fig. 4). An iron-constantain thermocouple provided the combustor inlet temperature. Chromel-alumel thermocouples were needed for the higher temperature engine stations. Calibration was accomplished prior to each run by means of a manually balanced potentiometer. The thermocouples were assumed to behave linearly. The calibration technique and accuracy information can be found in Fisher (Ref 6).

The combustor inlet temperature recorded was designated T_3. A control room gage was used to observe the temperature in the combustor just ahead of the catalyst. The combustor dome temperature designated T_d was recorded on the oscillograph. Two thermocouples were used to indicate the turbine inlet temperature which was T_4. One was connected to a gage to provide direct observation of the turbine inlet temperature. The output of the other was directed to the oscillograph to be recorded. The final thermocouple was located in the turbine exit section.

Pressure Measurement

Pressure transducers were used to measure pressure at various engine stations (Fig. 4). They were calibrated through the methods established by Fisher (Ref 6). Total

1. Combustor inlet Temperature, T_3
2. Combustor Temperature, T_5
3. Combustor Dome Temperature, T_d
4. Combustor Dome Pressure, P_d
5. Combustor Discharge Pressure, P_4
6. Combustor Inlet Pressure, P_3



7. Turbine Exit Pressure, P_5
8. Turbine Inlet Temperature, $T_{4\ gage}$
9. Turbine Inlet Temperature, T_4
10. Contact Point with Strain Gage
11. Static Pressure Taps for Mass Flow Measurement

Figure 4. Instrumentation Stations

pressure probes were used in most stations. In the other stations, static measurements were assumed to provide total pressures. All pressures were recorded on the oscillograph in the control room. One total pressure probe was located just before the combustor, P_3. Another designated P_d was located at the rear of the combustor at the dome of the liner. A total pressure probe, P_4, was located just upstream of the turbine inlet. Finally, there was a total pressure probe, P_5, located in the instrument section connected to the rear of the turbine housing. A barometer in the control provided ambient atmospheric pressure, P_∞.

Thrust

Engine thrust was measured through a force bar with strain gage elements attached to the test stand. Calibration was similar to the method described by Fisher (Ref 6) except that three, ten-pound weights were used. The engine itself was suspended from the top of the engine test stand so that it could freely swing and contact the cantilever mounted strain bar through the compressor housing. Thrust was recorded on the control room oscillograph.

RPM

The engine's rotating speed was measured by means of a photo diode, which was triggered by intermittent reflections from the compressor wheel. The compressor wheel was painted half white and half black to provide a sharp contrast. A DC light was shown on the compressor face to

provide a constant light source. The output of the photo diode passed through a frequency to voltage conversion circuit and was recorded on the oscillograph as well as displayed in the control room so the rotation of the engine could be monitored directly.

Mass Flow

The pressure difference across the bellmouth inlet to the compressor was recorded in inches of water on the oscillograph. This pressure was translated to the air mass flow rate, $\dot{M}_a$, by means of a chart developed by Kent (Ref 10). The calibration technique can be found in Reference 5.

Fuel Flow

Hydrogen fuel pressure downstream of the venturi was measured and recorded on the oscillograph. The upstream pressure can be calculated by knowing the pressure change across the venturi. A water manometer was installed in the control room for this purpose.

IV. Engine Run Procedure

To provide basic safety and consistancy, a procedure for operation of the engine was used. There were three primary phases involved: connecting the outside gas supplies, preparing the control room instrumentation, and final set up plus calibrations inside the test cell. At this point, the engine could be operated many times with only minor adjustments necessary between runs. During operation of the engine, the water manometer, which indicated the change in fuel pressure across the venturi, was read at various points and the value marked on the oscillograph paper. All other parameters were automatically displayed or recorded.

To start the engine, compressed gas was impinged on the turbine blades. Sufficient pressure was used to produce a rotational speed of 25,000 to 30,000 RPM. The hydrogen was then gradually introduced into the combustor to react with the air in the presence of the catalyst. The reaction would then propagate to the combustor dome. Indication of this occurrence was provided by a rapid rise of T_d shown by the control room temperature gage reaching about 1000F. The air start could then be disconnected and the engine would be self-sustaining.

After the engine was successfully maintained at idle conditions, the hydrogen fuel pressure was slowly increased

until the engine reached its maximum power setting. This point was defined by the attainment of either a turbine inlet temperature of 1800F or 120,000 RPM. These limits were set to prolong the life of the engine. The monolithic substrate, which the catalytic element was made from, could not sustain a temperature over 1800F without risking failure. The turbocharger bearings could not function at an RPM over 120,000 for any length of time. The high temperature coupled with excessive speed could also damage the turbine blades.

Normal shutdown procedure consisted of bringing the engine back to idle conditions and engaging the purge system to block the flow of hydrogen and allow nitrogen to pass through the fuel lines and the engine. The air-start system was reactivated to motor the engine facilitating cooling. The purge control could also be engaged in an emergency at any point during engine operation to cut off the fuel flow.

The general order of testing was to begin with the largest turbine housing with no nozzle which corresponded to the greatest flow area and proceed to the smallest housing and nozzle combination. The 1.0 A/R ratio turbine housing was attached to the engine providing an exit diameter of 2 3/4 in. Successive testing involved 2 1/2, 2 1/4, 2, and 1 3/4 in. diameter nozzles on the same housing. This scheme provided the shortest turn around

time between runs. This pattern was repeated with the .9, .8 and .7 A/R ratio housings in that order. Finally the fabricated turbine housing was attached to the engine for testing. The exit diameter was 2 1/2 in. and no nozzle was fitted.

V. Results

The engine demonstrated smooth operation in most configurations. The configurations using the 1 3/4 in. nozzle did not perform well with respect to the other nozzles. Generally, with the largest nozzles, the RPM limit was reached before the temperature limit. The smaller nozzles allowed the engine to reach the temperature limit without excessive rotation speed. However, the smaller nozzles required a higher turbine inlet temperature than the larger nozzle configurations to provide self-sustained operation. The fabricated turbine housing required much greater air-start pressure to reach operating speed than the other housings did. It also did not operate very smoothly at high temperature conditions causing vibrations which adversely affected the RPM measurement at these temperatures.

The original concept of the fabricated turbine housing was to reduce the weight of the engine by replacing the heavy standard cast-iron housing. It was hoped to use simple machine shop techniques for low cost and still obtain good performance. Because of the fabrication methods available, the housing thickness was constrained. The result was no appreciable savings in weight. Also, this turbine housing of simple construction demonstrated performance inferior to that obtained with the standard housings.

A large amount of data was generated through this testing. Those parameters usually associated with engine performance have been concentrated on. Values plotted are corrected to sea level standard conditions. Because of the constraints of 1800F turbine inlet temperature and 120,000 RPM, data could not be taken for the same range in all configurations. This is shown by the first set of graphs.

Figures 5, 6, 7 and 8 show the effect of temperature on RPM for each turbine housing used with every nozzle. There is a corner evident in the upper right-hand side of each figure. This shows where the runs were terminated because of reaching the temperature or RPM limit. The 2 and 2 1/4 in. nozzles show the best adherence to the constraints. The larger nozzles could have easily reached higher temperatures if the RPM restriction was relaxed. During an early run, the RPM was not indicating correctly and the engine was brought up to 1800F. Unfortunately, this overspeeding caused failure of the bearings. Similarly, it was possible to operate at turbine inlet temperatures in excess of 1800F. However, high temperature operation could result in damage to the turbine blades.

The temperature and RPM plotted a family of curves for each housing; each curve pertaining to a particular nozzle size. The newly fabricated housing was graphed with the .7 A/R housing, which it closely resembled in performance. All curves were smooth and they displayed the same trend.

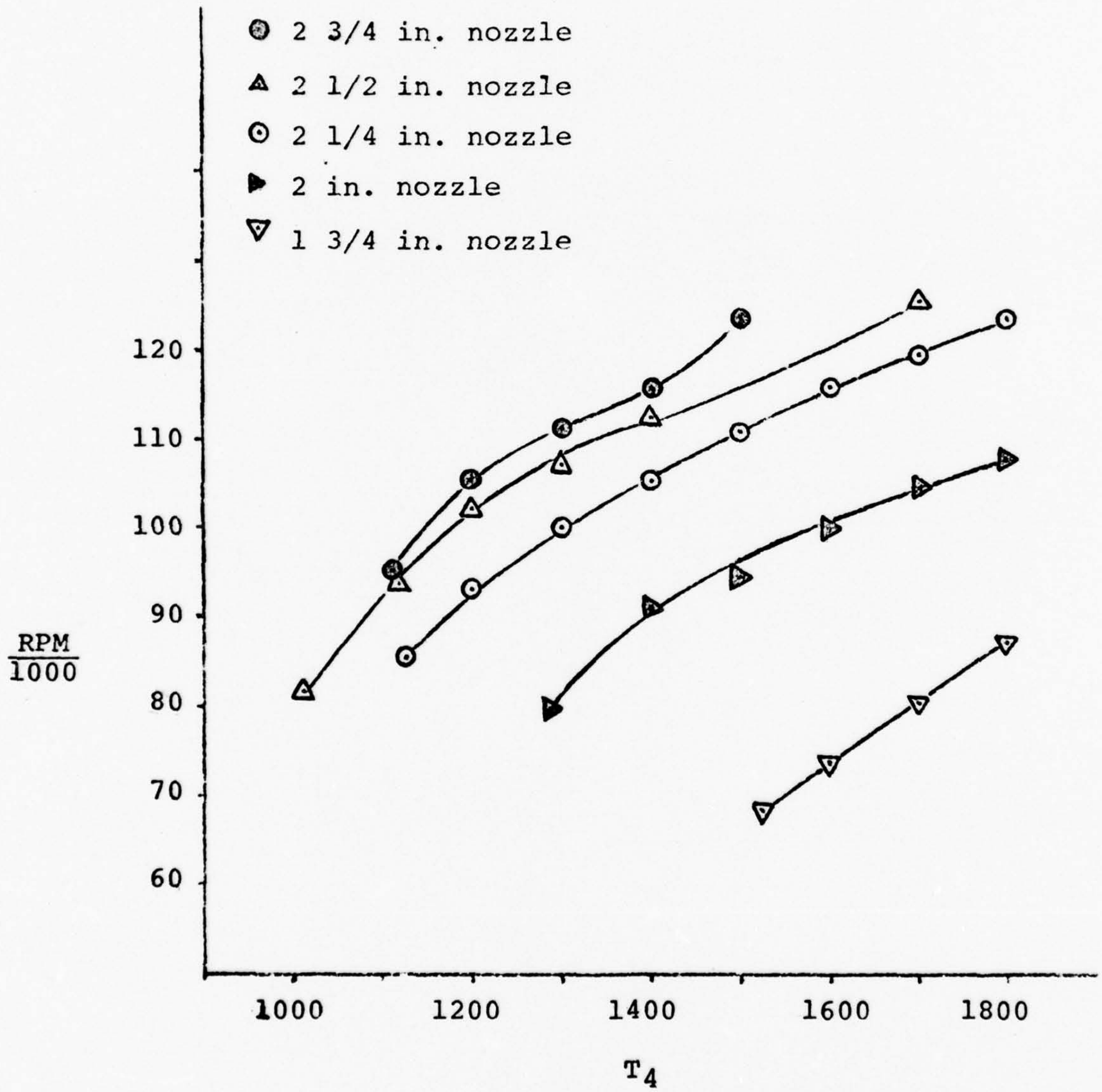


Figure 5. RPM Compared to Turbine Inlet Temperature for 1.0 A/R Ratio Housing.

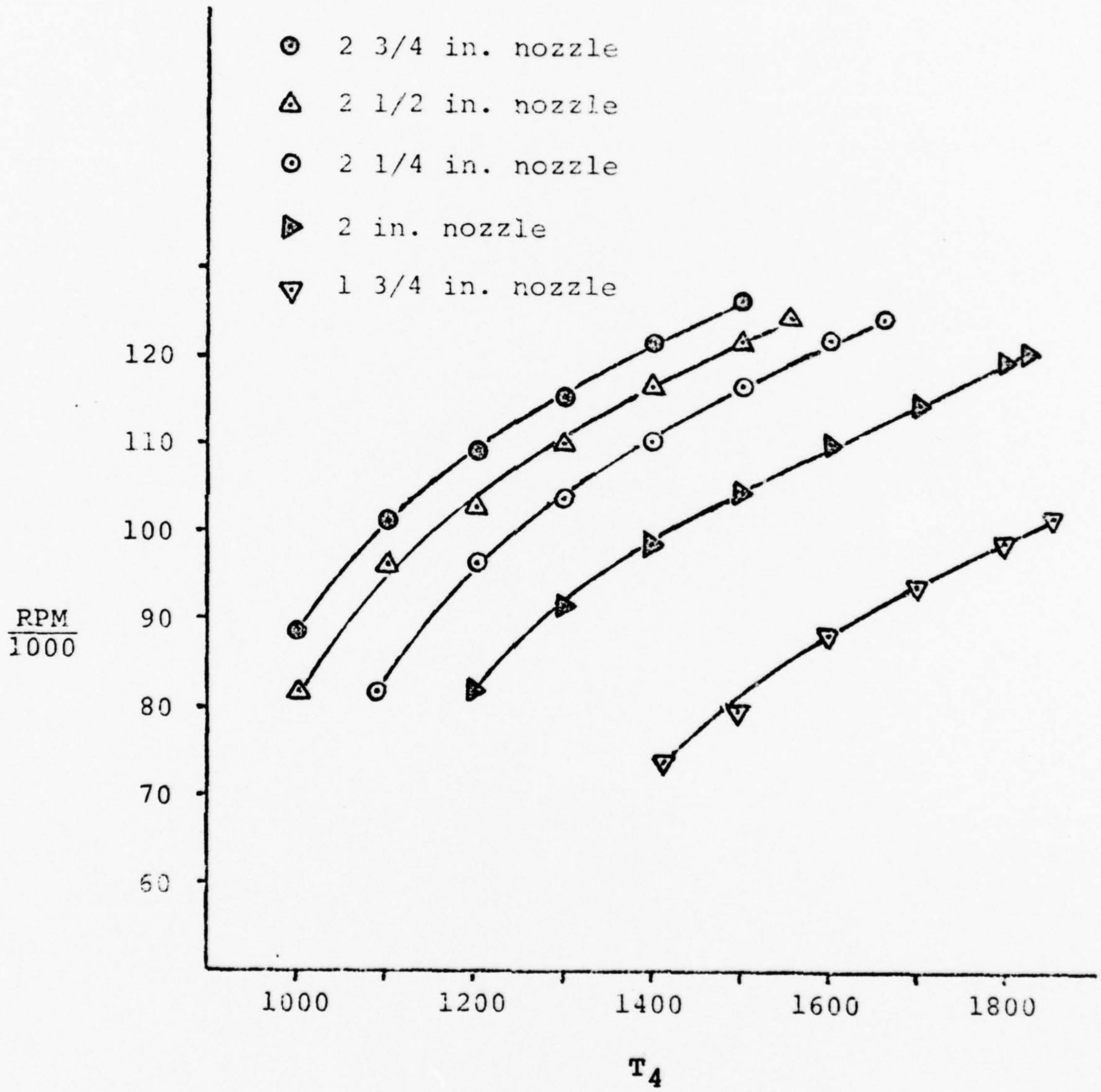


Figure 6. RPM Compared to Turbine Inlet Temperature for .9 A/R Ratio Housing.

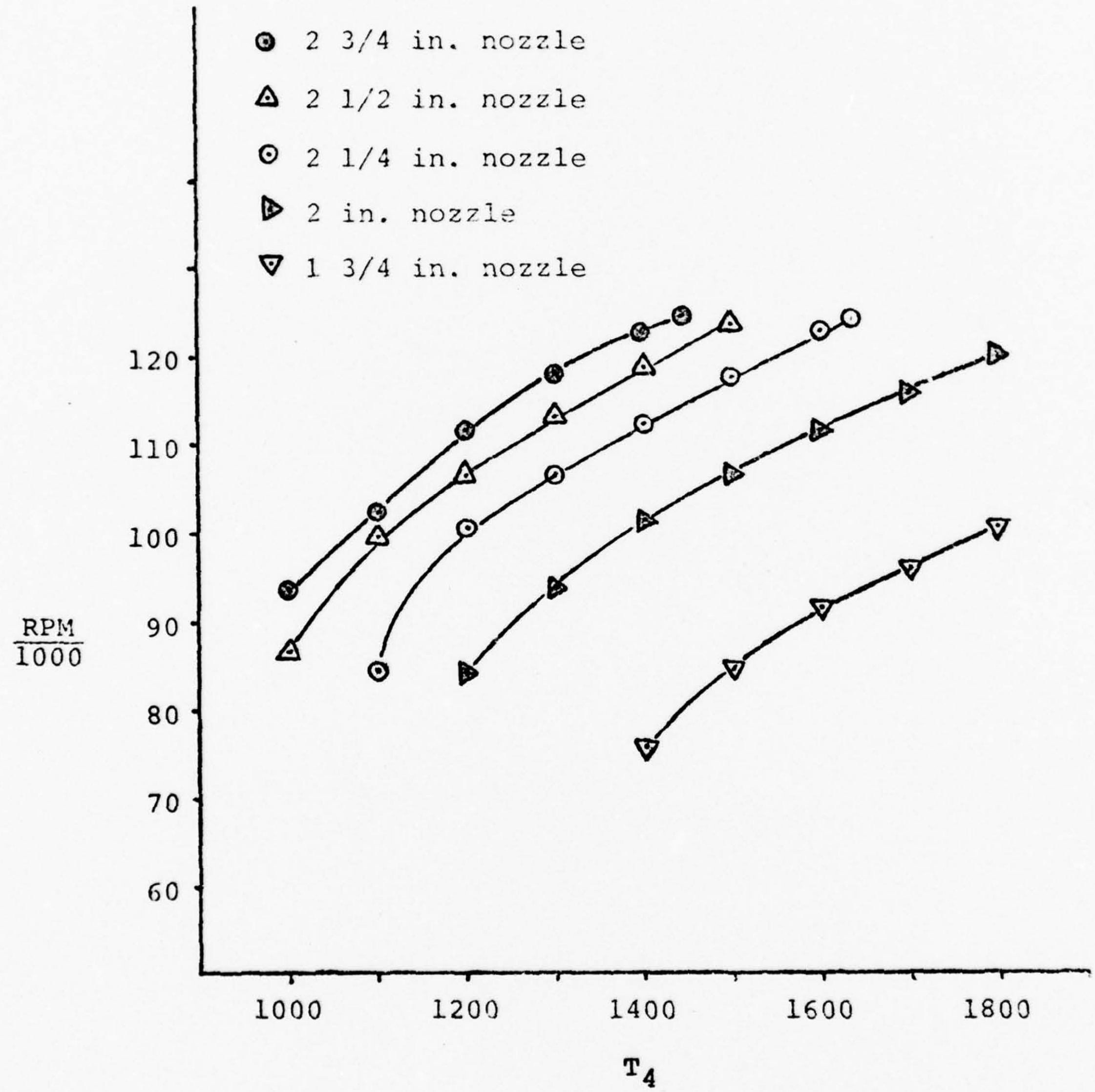


Figure 7. RPM Compared to Turbine Inlet Temperature for .8 A/R Ratio Housing.

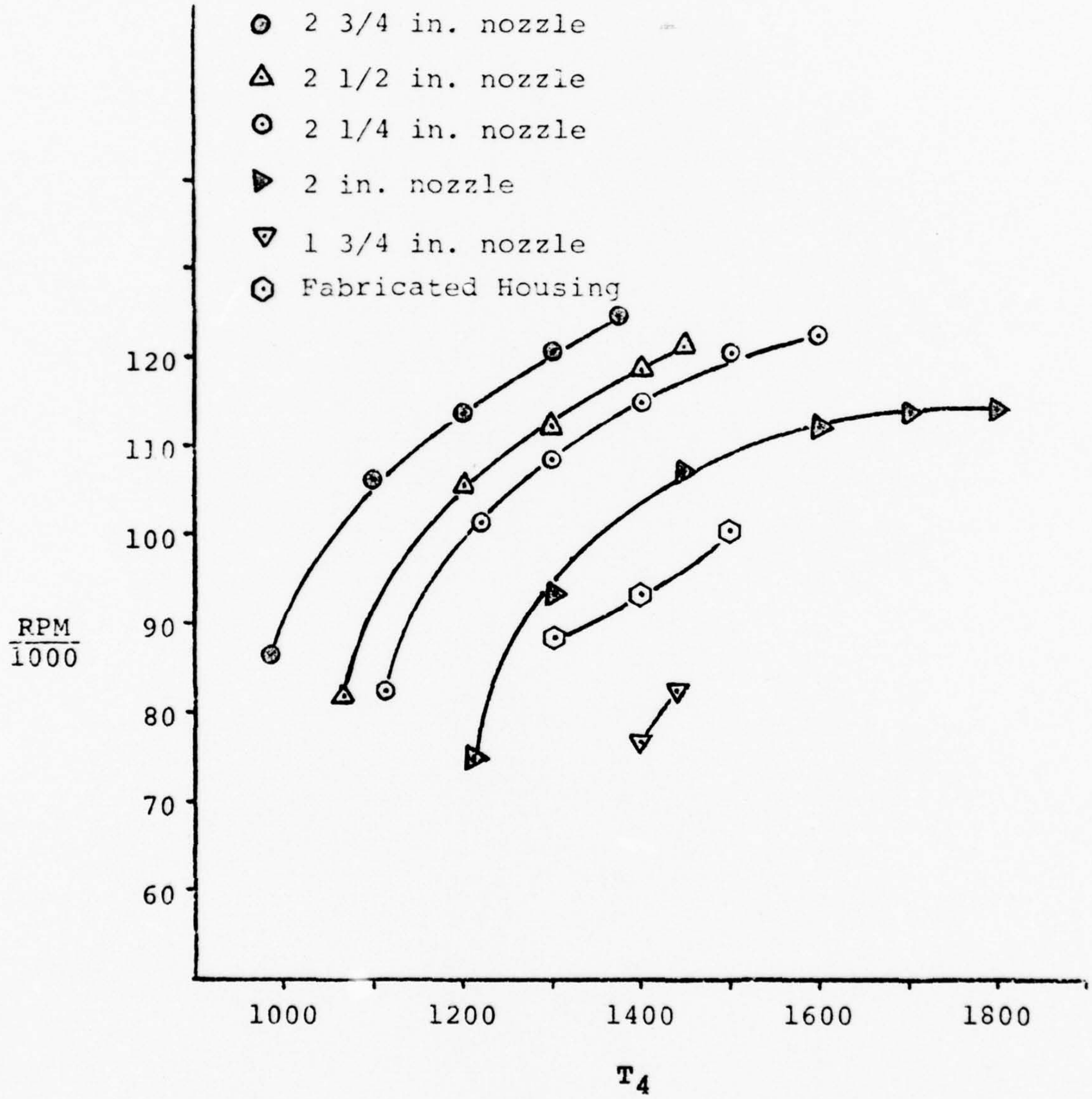


Figure 8. RPM Compared to Turbine Inlet Temperature for .7 A/R Ratio and Fabricated Housings.

As the nozzle size was decreased, the curve moved to the right, allowing higher temperatures to be reached for a given RPM. The crossover point separating RPM limited operation and temperature limited operation was between the 2 1/4 and the 2 in. nozzles for every standard housing.

Figure 8 shows two basic differences in the 1 3/4 in. nozzle on the .7 A/R ratio housing and the new housing from the rest of the data. The .7 A/R ratio housing with the 1 3/4 in. nozzle was very rough running. It could barely be kept running let alone taken up to temperature. In the case of the new housing, it was also rather rough running. In fact, the engine vibrated which caused the RPM to be inaccurate at the high end of the operating range.

Figure 9 shows the relationship between compressor pressure ratio and thrust for the various turbine housing and nozzle combinations. It was shown predictably that an increase in the pressure ratio had a similar effect on the thrust. The data points plotted in fairly smooth curves, limited in length by the operational constraints of temperature and RPM. The observed trend was for decreasing nozzle size to move the curves to the left toward a higher thrust per given pressure ratio. The effect of smaller turbine housings was to move the family of curves to the right. The highest thrust produced was 34 lb. with the .9 A/R ratio housing and the 2 in. nozzle. Generally, for each housing the best thrust was produced by the 2 and 2 1/4 in. nozzles.

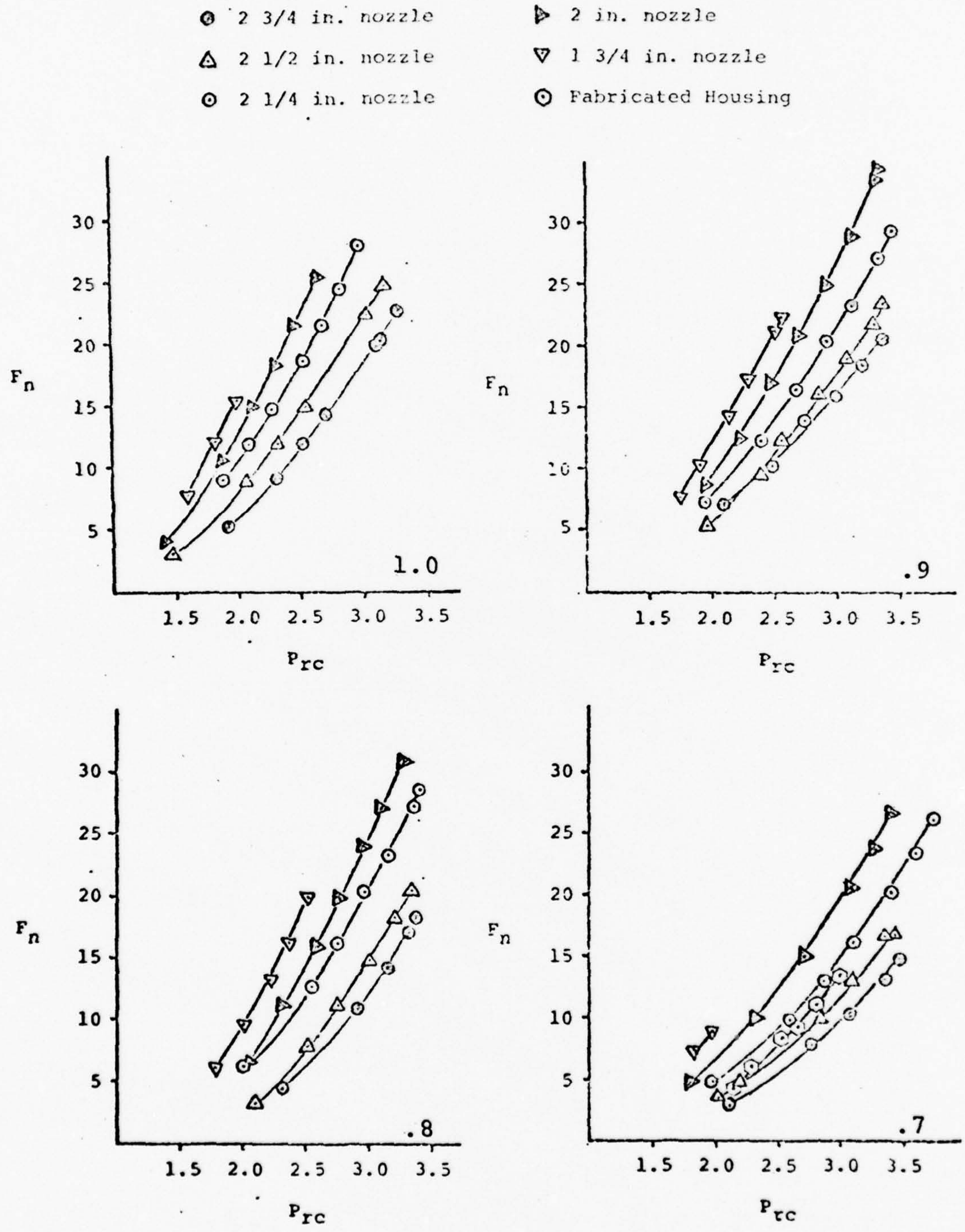


Figure 9. Compressor Pressure Ratio Related to Thrust and Engine Size.

The comparison of air mass flow and compressor pressure ratio is shown in Figures 10 to 13. The data did not always form perfectly smooth lines, but the basic trends were always consistant. They all show a high mass flow corresponding to a high pressure ratio. Lines for different nozzles on the same turbine housing tend to be very close together. The basic trend is for the curve to move to the upper left side as either nozzle or turbine housing size is decreased. The basic slope of the plots remains constant. Even the new sheet-metal housing fit in with the other curves. The plots were consistant with the compressor map for the Rajay turbocharger (Ref 11).

The last set of graphs (Figures 14 to 17) shows the effect of thrust on turbine inlet temperature. The data plotted in smooth curves nearly indicate straight lines of similar slope. The effect of nozzle size for all standard housings fit the same general pattern. From the line traced by the no nozzle configuration, the 2 1/2 in. nozzle gave a slightly higher plot. Then the 2 1/4 in. nozzle curve was slightly higher and indicated the peak values. Then the 2 in. nozzle plotted just under it and the 1 3/4 in. nozzle were well below the other curves. The fabricated turbine housing plotted very low on the scale and seemed to have a lower slope than all the other curves. On each graph theoretical results from the CARPET computer program (Ref 13) obtained for the Rajay turbocharger engine were plotted. These theoretical results compare rather closely to the data obtained experimentally.

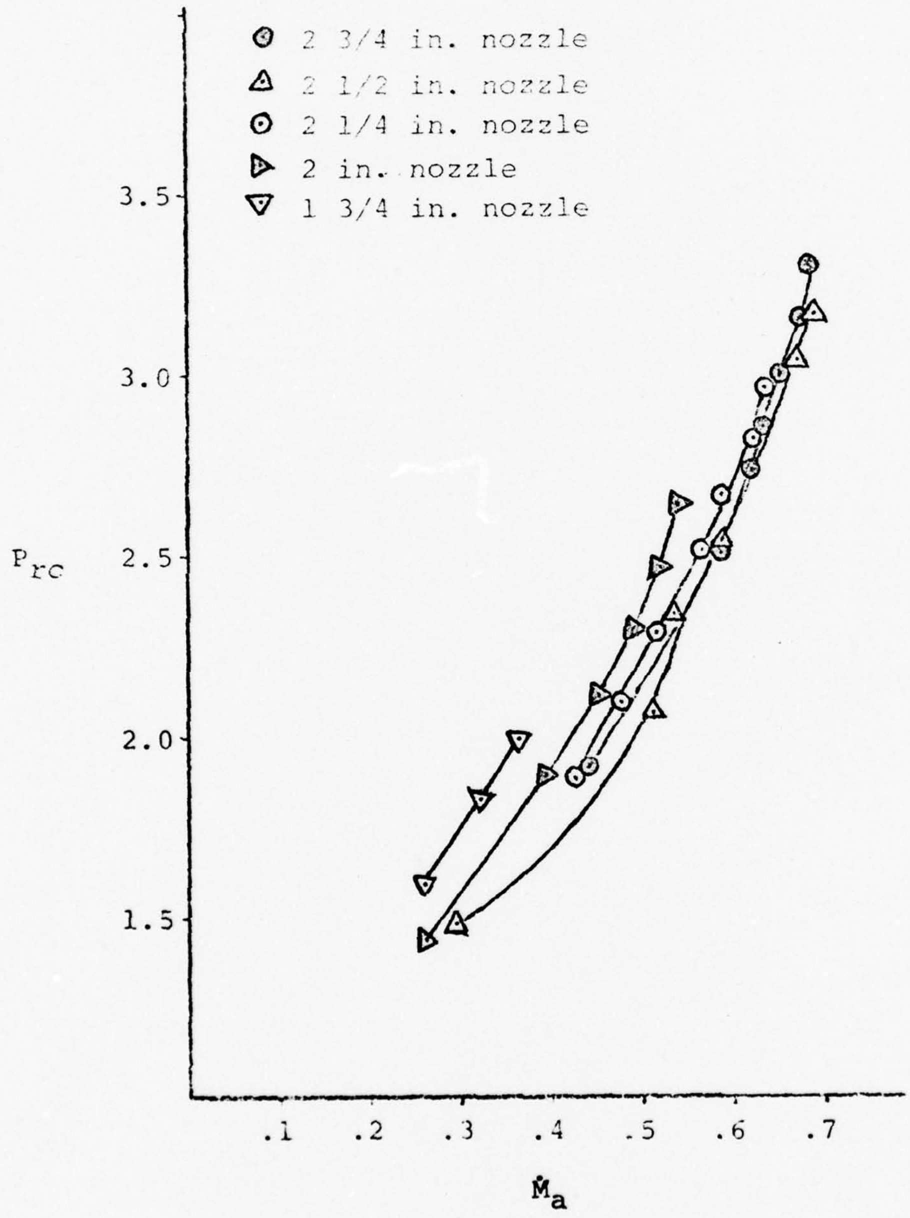


Figure 10. Compressor Pressure Ratio as a Function of Air Flow Rate for 1.0 A/R Ratio Turbine Housing.

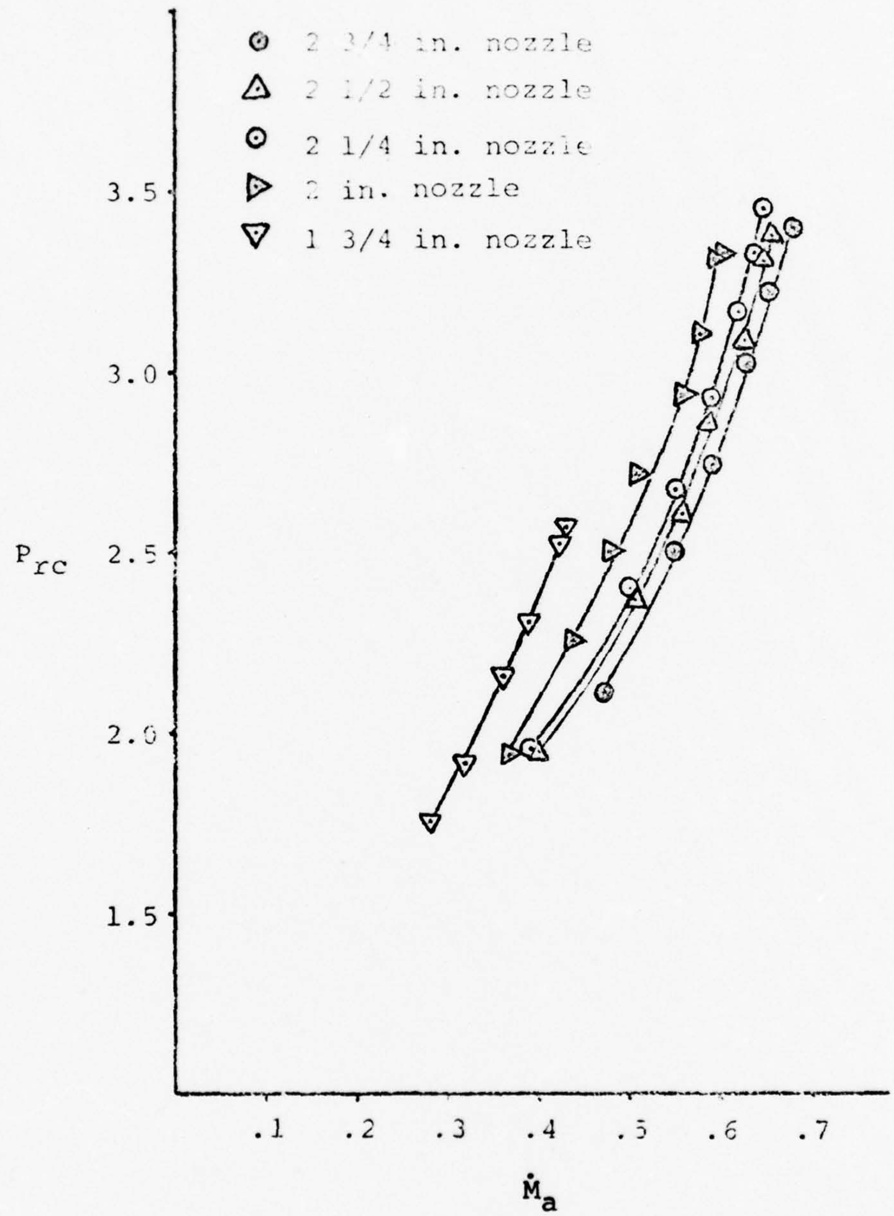


Figure 11. Compressor Pressure Ratio as a Function of Air Flow Rate for .9 A/R Ratio Turbine Housing.

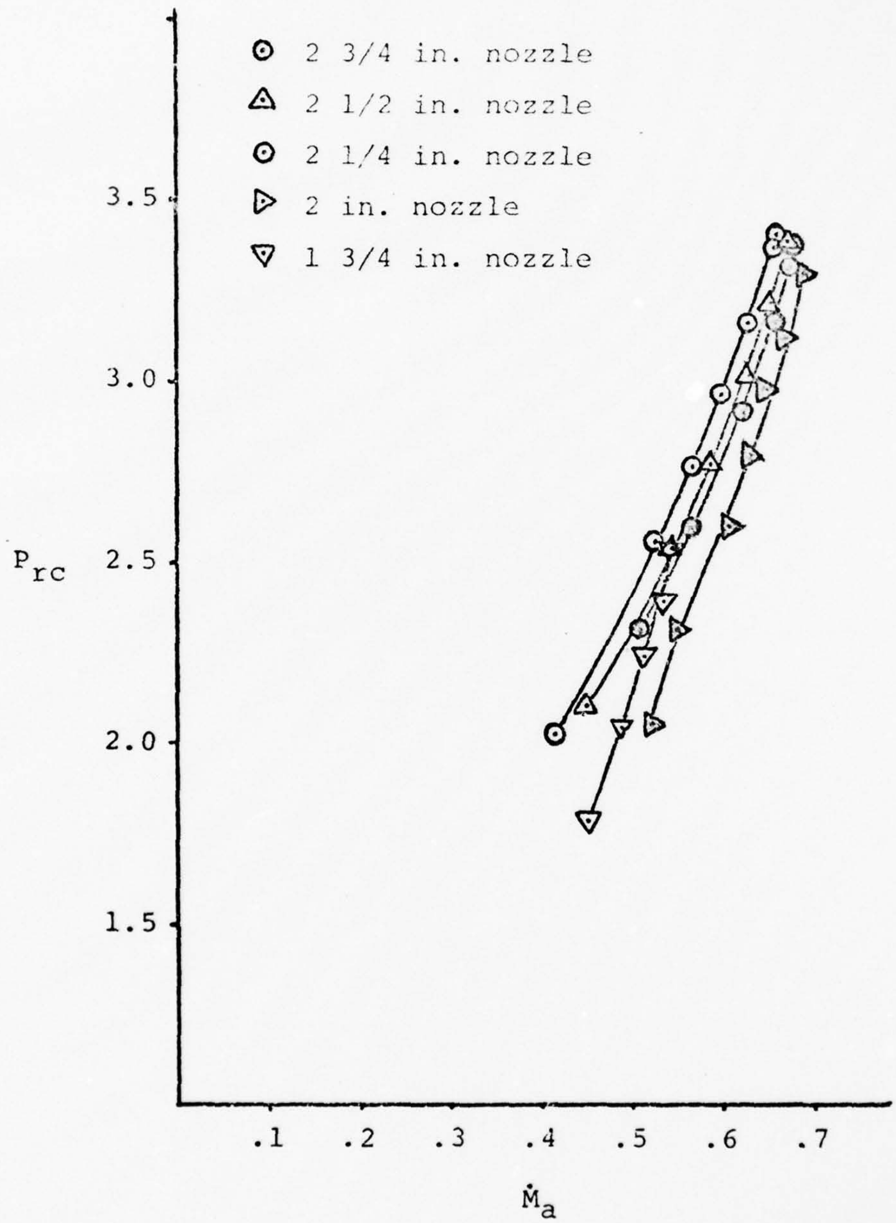


Figure 12. Compressor Pressure Ratio as a Function of Air Flow Rate for .8 A/R Ratio Turbine Housing.

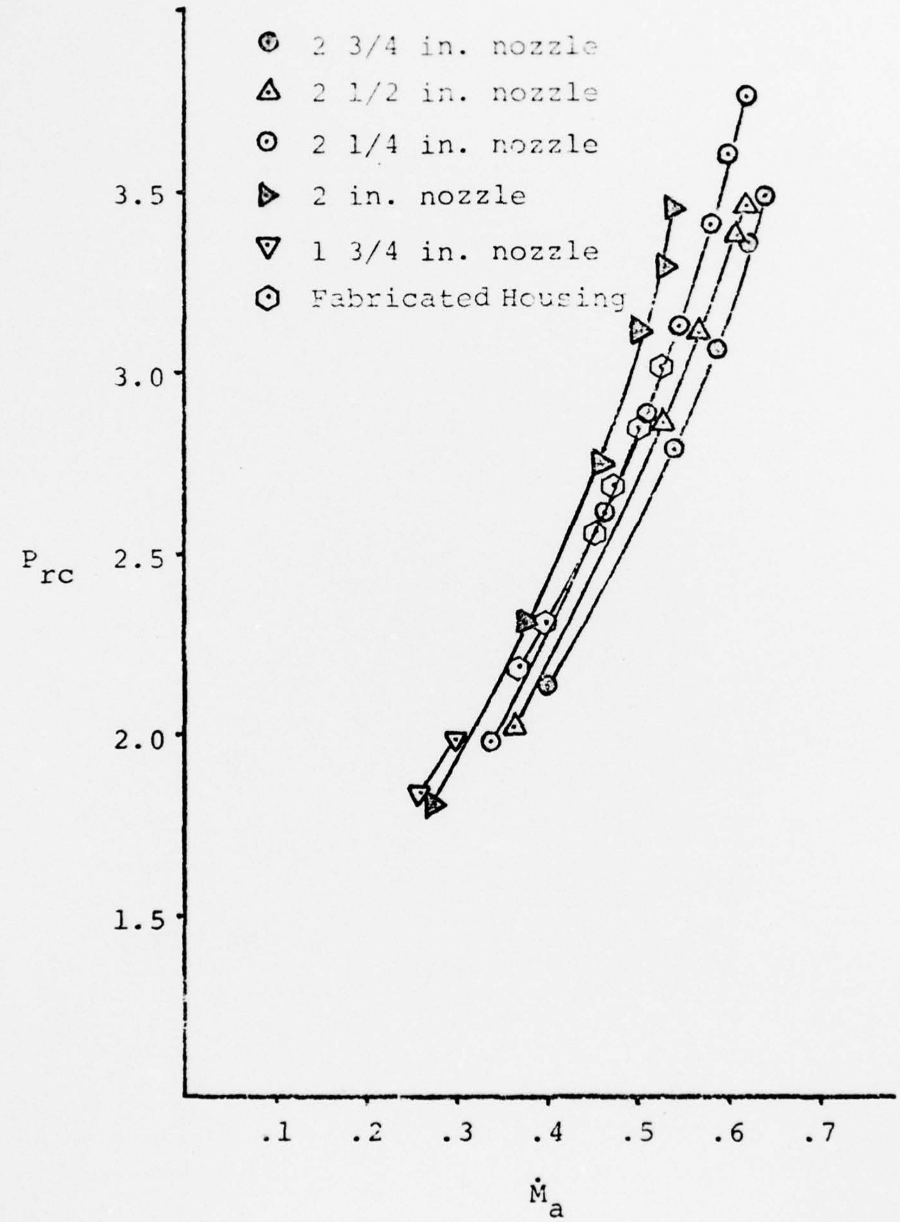


Figure 13. Compressor Pressure Ratio as a Function of Air Flow Rate for .7 A/R Ratio and Fabricated Turbine Housings.

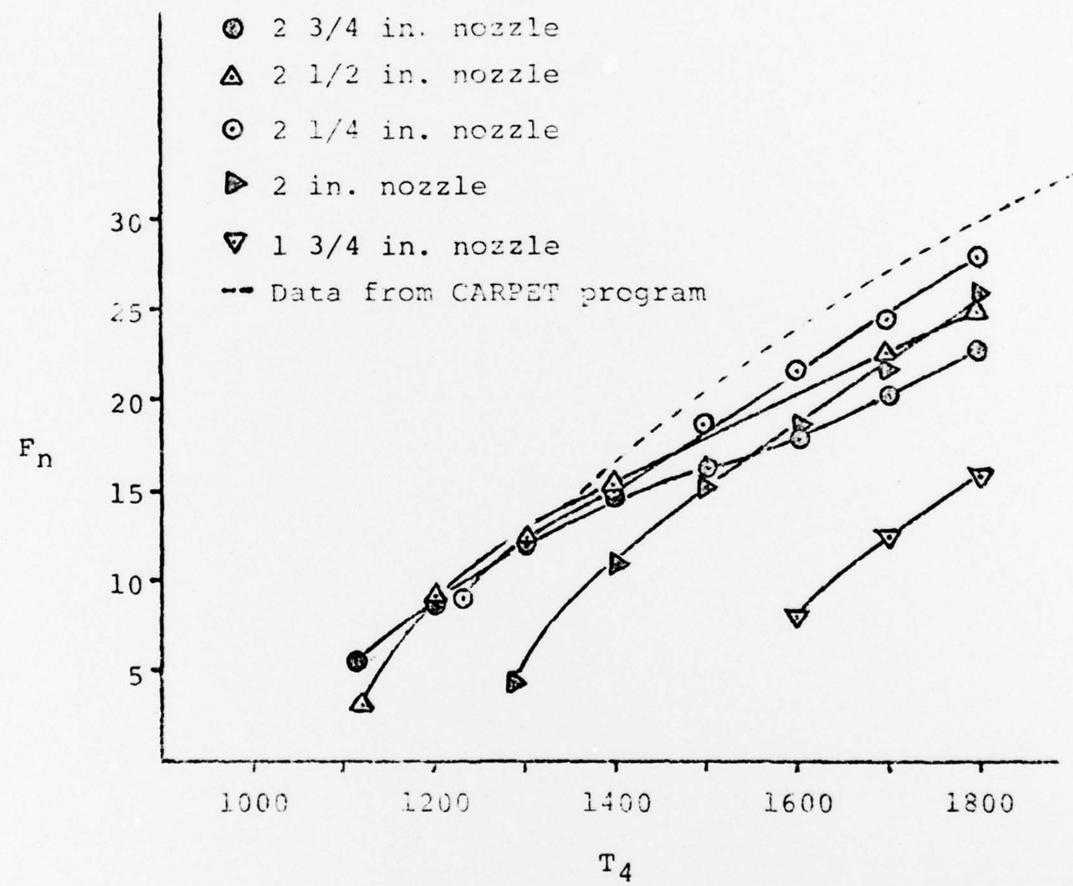


Figure 14. Thrust and Turbine Inlet Temperature Relations from Theoretical and Experimental Data for 1.0 A/R Ratio Housing.

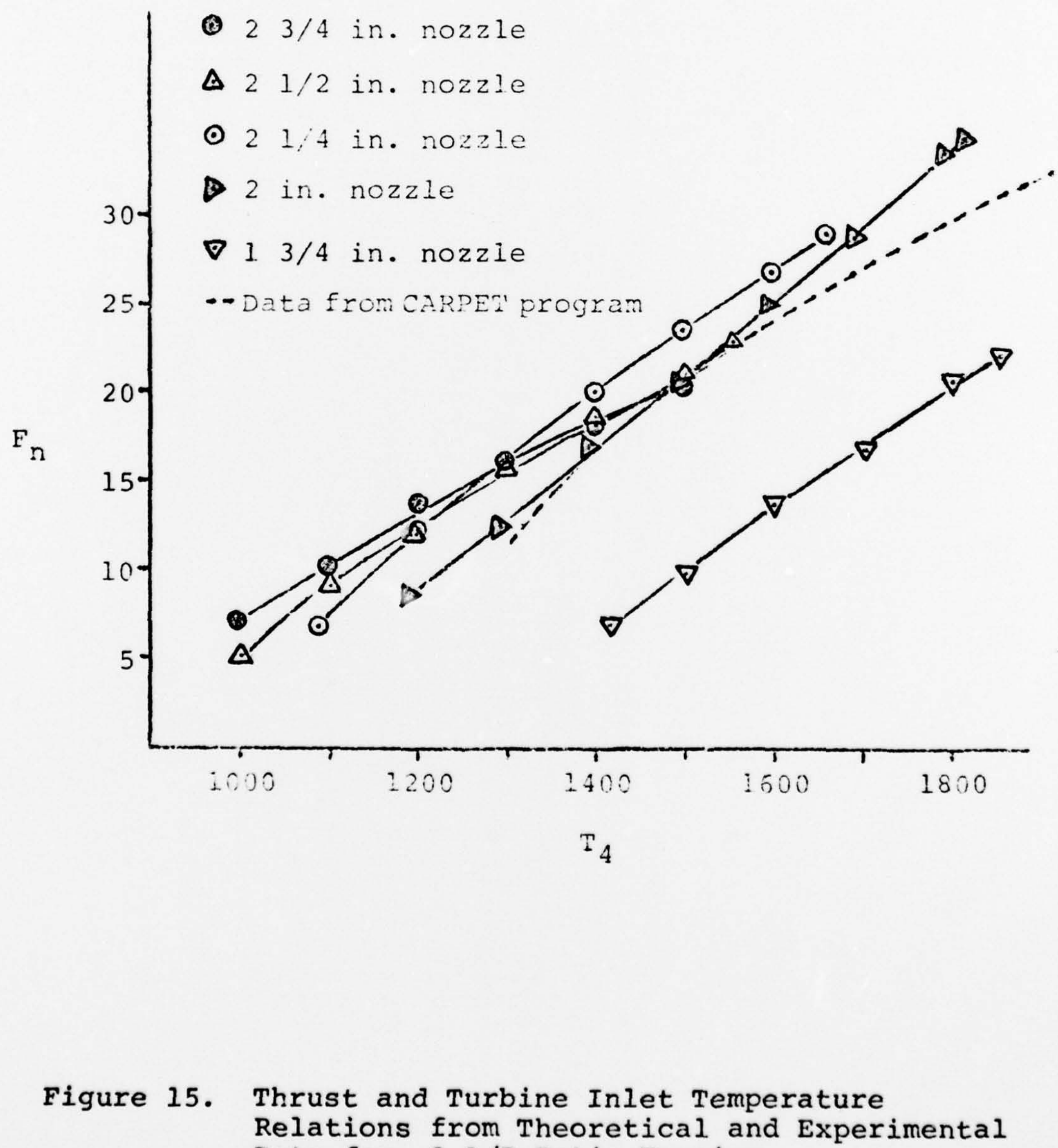


Figure 15. Thrust and Turbine Inlet Temperature Relations from Theoretical and Experimental Data for .9 A/R Ratio Housing.

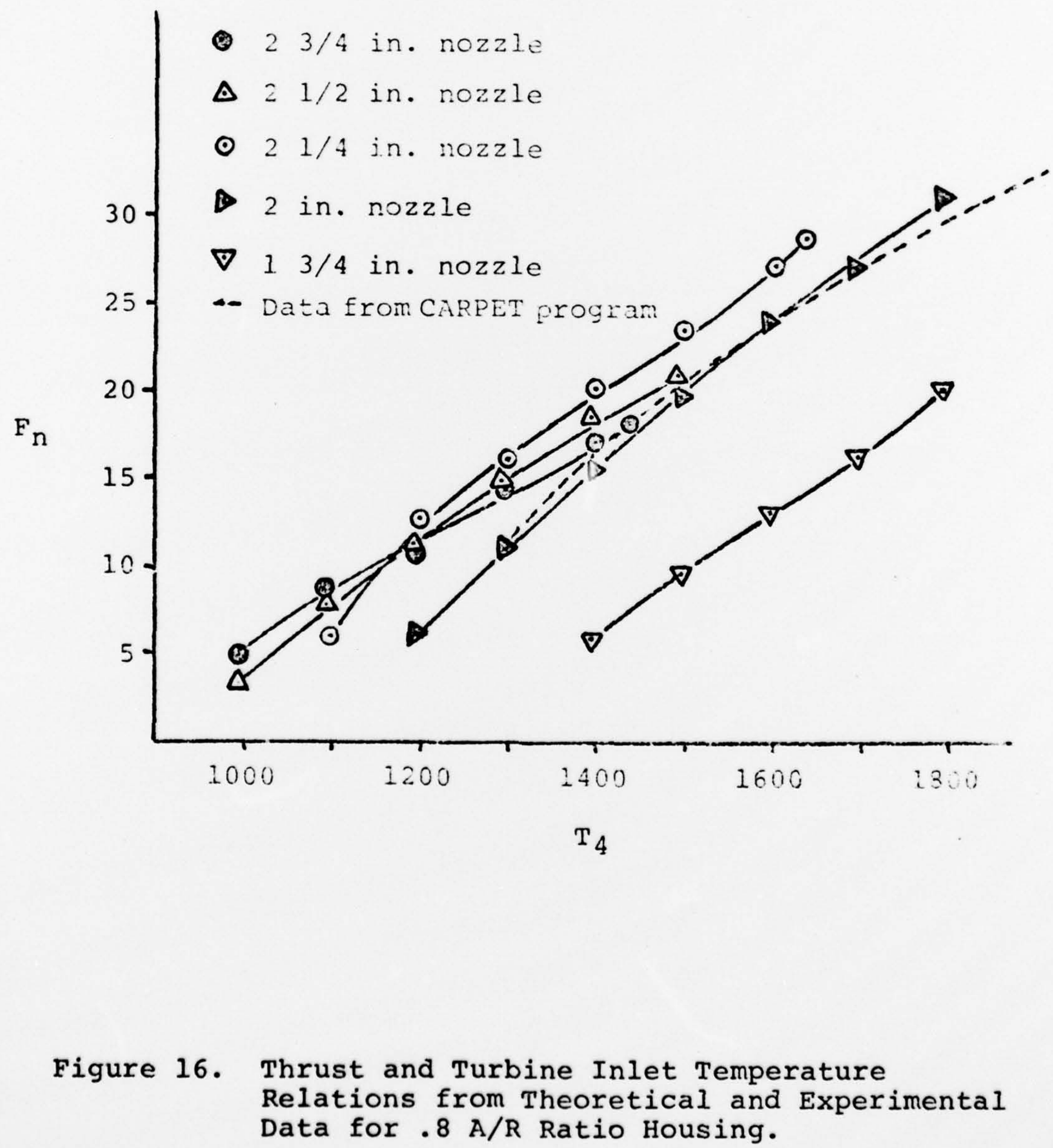


Figure 16. Thrust and Turbine Inlet Temperature Relations from Theoretical and Experimental Data for .8 A/R Ratio Housing.

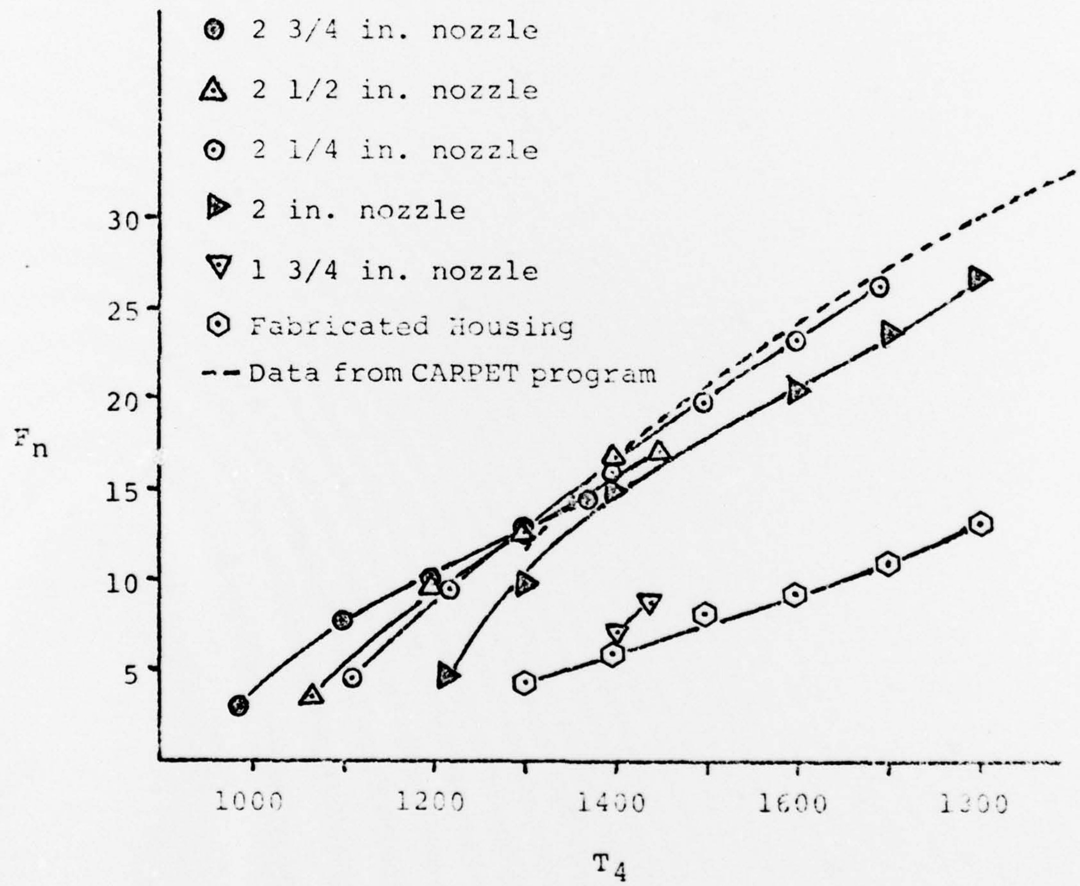


Figure 17. Thrust and Turbine Inlet Temperature Relations from Theoretical and Experimental Data for .7 A/R Ratio and Fabricated Housings.

VI. Conclusions and Recommendations

Conclusions

The catalytic turbocharger engine has been demonstrated to be quite workable using hydrogen fuel. The engine is stable and smooth running in various configurations. The .9 A/R ratio turbine housing coupled with the 2 1/4 and the 2 in. nozzles gave the best performance. A nozzle sized between these should deliver optimum performance. The performance data generated through this testing was reasonable and compared well with theoretical data provided through the CARPET program.

It was determined through the test data that smaller nozzle size allowed higher temperatures at a given RPM to be reached. Also, higher thrust for a given compressor ratio was achieved by reducing nozzle size. The engine, when equipped with nozzles larger than 2 inches in diameter, was restricted by RPM limits, and with nozzles 2 inches and smaller the limitation was turbine inlet temperature. Use of less restrictive RPM and temperature limits would produce better performance and may be possible for operation of short duration. However, running beyond the limit of 1800F and 120,000 RPM for extended periods invites failure.

The turbine housing fabricated from sheet metal did not provide desired weight reduction. Its inferior performance would not warrant its use except as a last resort.

More sophisticated fabrication methods would have to be employed to achieve weight reduction without sacrificing performance capability. It would have to be determined whether such weight reduction would balance out the increased cost.

Recommendations

The concept of a turbocharger engine is worth further work. Possible directions of attack would be to try installing an annular burner to clean up the engine geometry considerably. The catalytic element could possibly be used to initiate combustion of another fuel using a catalyst-fuel combination which provides low temperature reactions. Another method would be to use hydrogen to start the combustion reaction, then switch to another fuel.

As far as the laboratory set-up is concerned, the greatest improvements could be made in the area of instrumentation. Work could be done to make the instruments more reliable. An effective fuel mass flow measuring system that would be automatically recorded is also needed. An improvement in the RPM measurement may possibly be achieved by painting the inside of the bellmouth inlet to avoid reflections which can give misleading readings.

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APPENDIX A

Data Reduction

All necessary data should be recorded on the oscillograph paper. The general procedure is to first translate the chart displacements into appropriate values, then apply corrections or computations shown below to produce usable data. The deflection translations are shown in Table I.

The pressures were first adjusted from psig values to psia then corrected to sea level standard. The air flow rate was translated from the recorded deflection to inches of water and then converted to lb. per second using the curve developed by Kent (Ref 10) then corrected. Temperatures were not corrected. RPM and thrust were also adjusted to sea level standard conditions. Fuel flow was measured using the pressure value recorded and the venturi pressure difference noted from manometer readings. The equation used was developed by Jahnke (Ref 9). Corrections are based on the difference of ambient conditions from standard. This is expressed by the values θ and δ as used by Wolfe (Ref 14).

$$\theta = \frac{T_\infty}{519R} \qquad (1)$$

with T_∞ = outside temperature in R

$$\delta = \frac{P_\infty}{29.92 \text{ in. Hg}} \qquad (2)$$

with P_∞ = barometric pressure in in. Hg.

TABLE I

Oscillograph Parameter Values

Channel	Property	Value Per Inch Displacement
2	H_2 Pressure = P_{2H_2}	38.46 psig
6	Mass flow = $\dot{M}_a$	4 in. H_2O
7	Compressor Discharge Pressure = P_3	7 psig
8	Combustor Dome Pressure = P_d	7 psig
9	Combustor Discharge Pressure = P_4	7 psig
10	Combustor Inlet Temperature = T_3	100F
11	Turbine Inlet Temperature = T_4	400F
12	Combustor Dome Temperature = T_d	400F
13	Thrust = F_n	10 lb
14	RPM	24,000 RPM
16	Turbine Exit Pressure = P_5	1 psig

So then the corrected values in terms of the uncorrected measurements became:

$$P_c = \frac{P}{\delta} \tag{3}$$

$$\dot{M}_{ac} = \dot{M}_a \frac{\sqrt{\theta}}{\delta} \tag{4}$$

$$F_{nc} = \frac{F_n}{\delta} \tag{5}$$

$$RPM_c = \frac{RPM}{\sqrt{\theta}} \tag{6}$$

The pressure ratio was calculated using corrected values:

$$P_{rc} = \frac{P_{3c}}{P_\infty} \tag{7}$$

with P_∞ as atmospheric pressure in psia.

Fuel pressure was calculated using:

$$P_{1H_2} = P_{2H_2} + \Delta P_{H_2} \tag{8}$$

where P_{2H_2} = hydrogen pressure downstream of the venturi and ΔP_{H_2} = the manometer reading for pressure difference over the venturi in psia.

Hydrogen mass flow was determined by:

$$\dot{M}_{H_2} = .0025428 \left(1 - \frac{.023268\ h_w}{P_{1H_2}}\right)\left(\frac{P_{1H_2}\ h_w}{T_\infty^c}\right)^{\frac{1}{2}} \tag{9}$$

where $h_w = \Delta P_{H_2}$ in in. H_2O and T_∞ = test cell temperature in R.

VITA

Michael O'Brien was born on November 11, 1953 in Troy, New York. After high school in Albany, New York, in 1971 he attended the University of Notre Dame. He was awarded a Bachelor degree in Mechanical Engineering and was commissioned through the Reserve Officer Training Corps in 1975. The Air Force Institute of Technology became his first assignment in August, 1976.

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Performance data were taken for a small turbojet engine which is made up of a turbo supercharger and a catalytic combustor, which were originally intended for automotive use. The design employed the catalyst to promote a hydrogen reaction in air to power the rotating machinery. Several turbine housings each used with various nozzles were run on the engine to produce performance data. Using a turbine inlet temperature

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limit of 1800F and a rotating speed limit of 120,000 RPM, a maximum thrust of 34 lb. was recorded. Stable engine operation was observed in most configurations. Performance compared well with theoretical data supplied by the CARPET computer program.